Chapter 1

Semi-numerical simulations of Reionization

Numerous semi-numeric methods, which implement excursion set or similar formalism on the simulated matter density field are present. The models predict the effectiveness of production of ionizing photons and distribution of the ionized regions in the space. Relevant physics is incorporated in these simulations with a modest computational effort.

For different source model scenario visualization, N-body simulation of the evolving dark matter density field outputs is used. Simulation volume size is $[500/h]^3 = [714\,\mathrm{Mpc}]^3$ on each side. 6912^3 particles of mass $4.0 \times 10^7 M_\odot$ on a 13824^3 mesh were used and then it was down-sampled to a 600^3 grid. Spherical over density scheme is used to identify the halos in each redshift output of the matter distribution. The minimum halo mass used to model the reionization simulation was $2.02 \times 10^9 M_\odot$.

For the case of different dark matter models visualization, outputs of GADGET 2.0 N-body simulations for dark matter for a volume of $[71.68\,\mathrm{Mpc}]^3$ with 1024^3 dark matter particles is used.

The steps for constructing the ionization field at a given redshift via semi-numerical simulations (which has been used in the above two cases) can be listed as follows:

- Generating the dark matter density field
- Position and mass of the collapsed structure i.e halos is identified
- The halos are assigned with the ionizing photons production rate
- Next the ionization maps are generated and then converted into redshifted 21-cm brightness temperature fields.

Generating the dark matter density field and identification of the position and mass of the halos is accomplished using N-body simulations. It is presumed that the photons produced by a halo is proportional to its mass in most of the scenarios :

$$N_\gamma(M_h) = N_{ion}\frac{M_h\Omega_h}{m_p\Omega_m} \tag{1.1}$$

where N_{ion} represents the number of photons entering in the IGM per baryon in collapsed objects and it is a dimensionless constant, which may depend on various other degenerate reionization parameters including star-formation efficiency of a source, escape fraction of ionizing photons from these sources etc and m_p is the mass of a proton or hydrogen atom.

Next depending on which source model of the reionization scenario is considered, the HI density map and the ionizing photon density map, is constructed. The excursion-set formalism is used to construct the ionization map using these two fields at the desired redshifts. These density fields of photons and neutral hydrogen are generally constructed in a grid coarser than the actual N-body resolution. In the simulations which is used in this paper, case of this grid spacing is 1.19 Mpc, i.e. 600^3 cells. Identification of ionized regions is done as follows. Smoothing of the HI density and ionizing photon density map using sphere of radius R for $R_{min} \leq R \leq R_{max}$. R_{min} is the resolution of the simulation which is equal to 1.19 Mpc in this case which is the grid spacing and R_{max} is the mean free path of the ionizing photon(Rmfp).

Next, The Ionization map is built in the following steps. Say for any grid point "x",if the averaged ionizing photon density $\langle n_{\gamma(x)}(x)\rangle_R$ is greater than the averaged HI density $\langle n_{H(x)}(x)\rangle_R$ for any R, then one identifies that grid point as ionized grid. If any grid point doesn't satisfy this specification then an ionization fraction value equal to $X_{HII}(x) = \langle n_{\gamma(x)}(x)\rangle_R / \langle n_{H(x)}(x)\rangle_R$is assigned to that grid point. This is repeated for all grid points in the simulation volume and for all R within the allowed range. Later the conversion of ionization into 21cm BT map is done using the formula :

$$\delta T_b = x_{HI}(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right) \times \left(\frac{T_s - T_\gamma}{T_s}\right) \tag{1.2}$$

where $x_{HI}$is the neutral hydrogen fraction, δT_B is the fractional baryon overdensity, T_s is the spin temperature and T_{CMB} is the CMB temperature. Here it is assumed that $T_s > T_{CMB}$.

1.1 Types of Dark matter models

1.1.1 Cold dark matter model:

Most simulations that are out there at present day consider the dark matter to be of cold dark matter type. The initial condition of the universe is conceived as smooth and nearly homogeneous. In the CDM models, the small perturbation imprinted in the density field grow via gravitational instabilities and merge with each other leading to the formation of complex structures. The CDM particles doesn't diffuse out of the lumps hence lumps exist in small scale as well as large scales. These lumps collapse with cosmic time and lead to the formation of the ionizing sources. Here the structures begin to form very early and this results in production of ionizing photons at early stage.

1.1.2 Warm Dark matter model:

Recently an alternative dark model to the CDM model is being considered and that is Warm Dark Matter model. This model suggests that initial perturbations below a certain mass cannot collapse and hence the formation of ionizing sources is pretty late. This is because the temperature of the dark matter particle at decoupling can cause the dark matter particle to escape from and erase the underlying density fluctuation. This results in slow formation of structures that are hosts for the ionizing sources which impact the reionization history.

1.2 Types of source Models:

1.2.1 Ultraviolet photons from galaxies (UV):

Most reionization models presume that the collapsed dark matter haloes are the places where ionizing photon emission sources are formed. The galaxies that are residing in the these haloes to be the significant sources of ionizing photons. The information about the high redshift photon sources and the characteristics of their radiation is not completely known because of the unavailable data, so it is assumed that the total number of ionizing photons emitted by the galaxies in the halo of mass M_h

$$N_\gamma(M_h) = N_{ion} \frac{M_h \Omega_h}{m_p \Omega_m} \tag{1.3}$$

N_{ion}, represents the number of photons entering in the IGM per baryon in collapsed objects and it is a dimensionless constant and m_p is the mass of a proton or hydrogen atom. Reionization simulations like semi-numerical or radiative transfer, which adopt this kind of model for the production of the major portions oftheir ionizing photons generally produce a global “inside-out” reionization scenario.

1.2.2 Uniform ionizing background (UIB):

At high redshifts, the population of galaxies that are observed cannot hold the universe ionized unless there is a substantial change in ionizing photon’s escape fraction with growing redshift or galaxies that can not be observed by today’s telescopes contribute a significant proportion to the overall ionizing photons . Another explanation may be that if sources such as active galactic nuclei or X-ray binaries were normal in the early period of the Universe, this would result in a more or less consistent ionizing background. The ionizing photons (X-ray in nature) emitted by these can easily escape from host galaxies and can fly long distances before ionizing hydrogen .

Such kind of source are modeled as a completely uniform ionizing background, providing the same amount of ionizing photons at every location. It will contribute to a global "outside-in" reionization if the amount of ionizing photons from this kind of source were significant $\geq 100\%$.

1.2.3 Power law dependent efficiency (PL):

Here it is presumed that the amount of UV photons produced by haloes follows a power law relation with their mass:

$$N_\gamma(M_h) = M_h^n$$

In such forms of source model, haloes with higher mass emit comparatively more ionizing photons, resulting in fewer but larger ionized areas. This model refers to a scenario in which reionization is guided by unusual, bright sources, such as quasars. But the number density of quasars is not estimated to be sufficient to cause reionization at high redshift Madau$_1$999, $Majumdar_2 015$.

Chapter 2

Effect of different Reionization models on 21 cm signal

In order to study the effect of source model on 21 cm brightness temperature, different scenarios of reionization are established by combining different source types. In this study, four different reionization scenarios were taken into account to study the effect on 21 cm brightness temperature maps. So any dissimilitude in the 21-cm brightness temperature signal across different reionization scenarios is entirely due to the types of sources, and not due to the underlying matter distribution. Additionally, we also study how will reionization change if the nature of dark matter is different, via visualization tool.

2.1 Cold Dark matter and Warm Dark matter scenarios:

Two different types of dark matter models effect on the 21cm BT map is visualized. The reionization history that is considered is from redshift z - 10 to z - 4. In cold dark matter, the ionizing sources are formed early, and hence the reionization of the neutral hydrogen will be completed earlier compared to that of warm dark matter. Since in warm dark matter the ionizing sources form a later time, the reionization is completed quite late compared to that of cold dark matter model.

Redshift z	$\bar{x}_{HI}$ (CDM)	$\bar{x}_{HI}$ (WDM)
10	0.842	0.943
9	0.709	0.877
8	0.473	0.749
7	0.111	0.509
6	0.002	0.133
5	0.000	0.004
4	0.000	0.00

Table 2.1: Table represents mass averaged neutral fraction $\bar{x}_{HI}$ at corresponding redshift z, for the dark matter models, for which the visualization is created.

2.2 Fiducial reionization scenario:

In Fiducial reionization scenario, 100% of ionizing photons are emitted from the galaxies residing in dark matter haloes, whose mass is greater than 2.02 $\times\ 10^9 M_\odot$ .It is presumed that the amount of UV photons produced by a galaxy is proportional to equation 1.3.Hence power law (PL) is one here. All the photons emitted are considered to be ultraviolet photons. This results in global inside-out reionization topology. The recombination rate here is considered to be uniform.

2.3 Clumping Reionization scenarios:

The clumping reionization scenario is same as the fiducial reionization scenario, i.e 100% of ionizing photons are emitted from the galaxies residing in dark matter haloes, but here the recombination rate is taken as non-uniform and density dependent.

2.4 UIB dominated reionization scenario:

In UIB dominated reionization scenario, 20% of the ionizing photons are considered as ultraviolet photons which are emitted from galaxies residing in the dark matter haloes and 80% of the ionizing photons are considered to be emitted from hard X-ray sources such as active galactic nuclei/ X-ray binaries. Here the recombination rate is considered to be uniform.

2.5 Power Law reionization scenario:

In Power law reionization scenario It is presumed that the amount of photons produced by the haloes governed by a power law

$$N_\gamma(M_h) = M_h^n$$

In this reionization scenario , higher halo mass haloes, emits comparatively more ionizing photons. The recombination rate here is considered to be uniform.

Reionization scenario	UV	UIB	PL(n)	Non uniform recombination
Fiducial	100%	-	1.0	No
Clumping	100%	-	1.0	Yes
UIB Dominated	20%	80%	1.0	No
PL 3.0	-	-	3.0	No

Table 2.2: The contribution of different sources in various reionization scenarios.